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The Effect of Slug Material on the Behavior of Small-Caliber Ammunition

by Joseph South, Aristedes Yiournas, and Michael Minnicino

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14. ABSTRACT
The drive to produce environmentally friendly “green” ammunition has shifted focus to alternate materials for the lead cores in small-arms ammunition. Candidate materials such as tungsten-nylon and tungsten-tin have been evaluated as possible replacements. This research is aimed at evaluating the response of the candidate materials as well as the current M855 “lead” round. Experiments were conducted on sheathed and unsheathed slug samples to determine their compressive response. It was found that each material exhibited a unique mechanical response. Finite-element simulations were generated to evaluate the relative response of each material during launch in a weapon with a linear rifling profile. Details of the experimental testing, generation of the models, and results of the analyses, as well as potential ramifications to bullet behavior, will be presented.

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1. Introduction

Small-caliber projectiles, such as the M855 ball round, are some of the simplest munitions in the U.S. Army inventory. The M855 projectile (*1*) depicted in figure 1 is comprised of three components: a lead-antimony slug, a steel core penetrator, and a copper jacket; and is similar to the ammunition that has been used for the last century. This ammunition is used in service and training for the M16A2/A3/A4, the M4, and the M249 weapons.

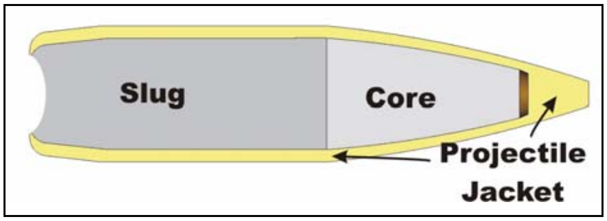

Figure 1. The M855 projectile.

The U.S. Army has a program to investigate alternative "green" materials to replace the slug and thus reduce the risk to the environment (*2*). These materials are to be a drop in replacement for the current lead-antimony (Pb-Sb) slug material. To match aeroballistic performance, candidate materials are to possess the same density as the Pb-Sb. During the program, a double blind study was conducted to evaluate the performance of candidate slug materials that were provided by industry. This study selected down to five candidates (*3*). Tungsten-nylon (W-Nylon) and tungsten-tin (W-Sn) were candidate material solutions.

Previous jump testing has shown that changes in the slug material from Pb-Sb to W-Nylon can dramatically alter the down-range behavior of the projectile. While jump is an indirect measure, it provides insight into the in-bore mechanics (gun/projectile interaction) of the system. For a given type of cartridge coupled with a particular barrel fired under similar conditions, the jump is relatively constant. While the round will not impact the same spot each time, this spread or dispersion is a measure of precision, whereas the average jump for a group of projectiles fired from the same barrel can be compared to infer changes in in-bore mechanics. Figure 2 shows the results of two types of M855 projectiles, tungsten/nylon and lead, shot from the same barrel. Each point on the graph shows the average jump obtained from 60 rounds. It can be seen from the figure that the lead rounds jump in a downward direction, while the W-Nylon rounds jumped in an upward direction. The difference in jump is on the order of 4 mrad.[*] This is a significant deviation in the behavior that is an order of magnitude larger than the system precision. The

[*]A milliradian (mrad) is 1/1000th of a radian.

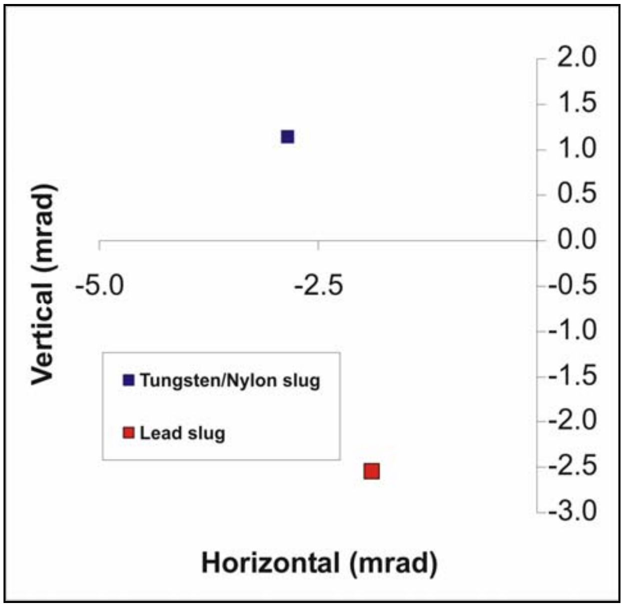

Figure 2. Average jump from 60 round groups for several types of M855 projectiles fired from a single M16A2 barrel (*4*).

dispersion of the M855 projectiles is typically less than 0.3 mrad. While this type of testing does not show how the launch mechanics differ in the system, it does show that the mechanics changed with the slug material change.

This report evaluates the response of two green materials as well as the current Pb-Sb round. Experiments were conducted on sheathed slug samples to determine their compressive response. It was found that each material exhibits a unique mechanical response. Finite-element simulations were generated to evaluate the relative response of each material during launch in a M16A2/A3/A4 rifle with a linear rifling profile. Details of the experimental testing, generation of the models, and results of the analyses, as well as potential ramifications to bullet behavior, will be presented.

2. Experimental

2.1 Experiments

Experiments were conducted to evaluate the response of the lead and green ammunition candidate slugs in a sheathed test environment (*5*). Completely fabricated 3-piece, M855 style, projectiles that contained the respective slugs were procured from production runs at Lake City Army Ammunition Plant in Independence, MO. A total of five different green projectiles were evaluated. Further study showed that these five were comprised of three W-Nylon and two W-Sn materials (*3*). Prior to testing, each projectile was prepared with a surface grinder. The projectiles were ground in order to remove the boattail and the ogive section ahead of the cannelure of the projectiles. This resulted in only the cylindrical section of the projectile remaining with the slug material being sheathed by the original copper gilding jacket. The final height of the sheathed test was 0.375 in. This corresponded to a length over diameter (L/D) ratio of 1.67. A schematic of this arrangement is shown in figure 3. The arrows in the figure denote the loading direction in the test. In this testing arrangement, only the slug material was in compression, e.g., the jacket was allowed to be a free surface.

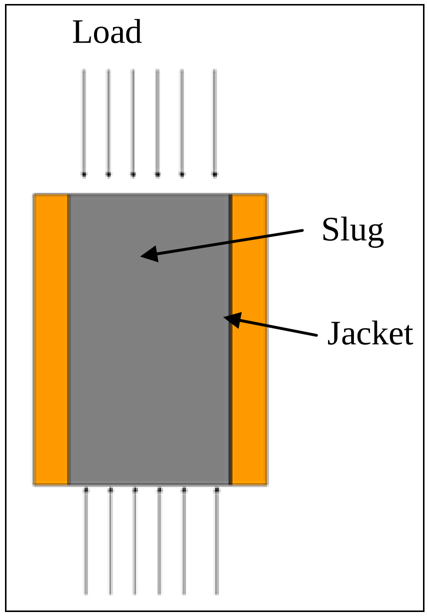

Figure 3. Schematic of the testing arrangement showing the sheathed slug. The arrows denoted the loading direction.

The tests were performed using an Instron screw-driven test frame. A testing jig was used that consisted of upper and lower steel platens with a 0.182-in diameter punch on each end. Attached to the punch was a small alignment collar that assisted in the alignment of the sample during the initial test setup. Once an acceptable amount of preload was established, the collar was shifted away from the test sample. This was done to avoid generating any potential confinement on the ends of the copper jacket. A pair of MicroMeasurement strain gauges were bonded 180° apart on the outer diameter of the jacket in order to acquire hoop and axial strain.

Figure 4 is a picture of the test setup showing the steel platens, alignment collars, and the strain gauges on the sheathed sample. The white object in the picture is a piece of rigid paper that was used to hold the lower alignment platen up during the initial test setup. The paper was removed prior to commencing the test.

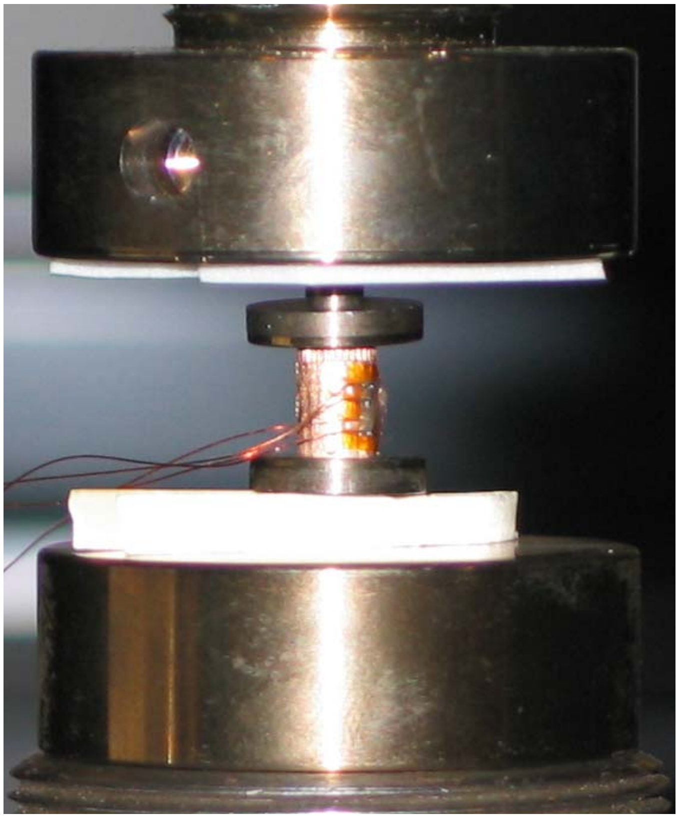

Figure 4. Picture of the test setup showing the steel platens, the alignment collars, and the strain gauges mounted onto the sheathed sample.

All experiments were conducted in displacement control at the rate of 0.05 in per minute. Ten samples of each of the three slug material types were tested. The test was run until either the sheath completely failed or until the sample buckled. Load, displacement, strain, and time were recorded during the test.

2.2 Experimental Results

The averaged results of the experimental data for each slug material are plotted in figure 5. The figure shows a substantially different response for each of the three materials. These experiments indicate that to achieve a given level of hoop strain in the jacket W-Nylon requires the highest loads while Pb-Sb requires the lowest. This behavior can be directly attributed to the yield strength of the respective core materials. Table 1 shows the experimentally obtained modulus, yield strength, and Poisson's ratio for the three different slug materials. It is shown in the table that Pb-Sb and W-Nylon have roughly the same modulus; however, the yield strength can vary by a factor of 4 between the Pb-Sb and the W-Nylon. It is a possibility that Poisson's ratio is affecting the results in figure 5 as well. The Poisson's ratio for the W-Nylon and the W-Sn is nearly identical but the average response in figure 5 shows that the W-Sn with a yield strength nearly half of the W-Nylon required less load to achieve the same level of hoop strain. Clearly,

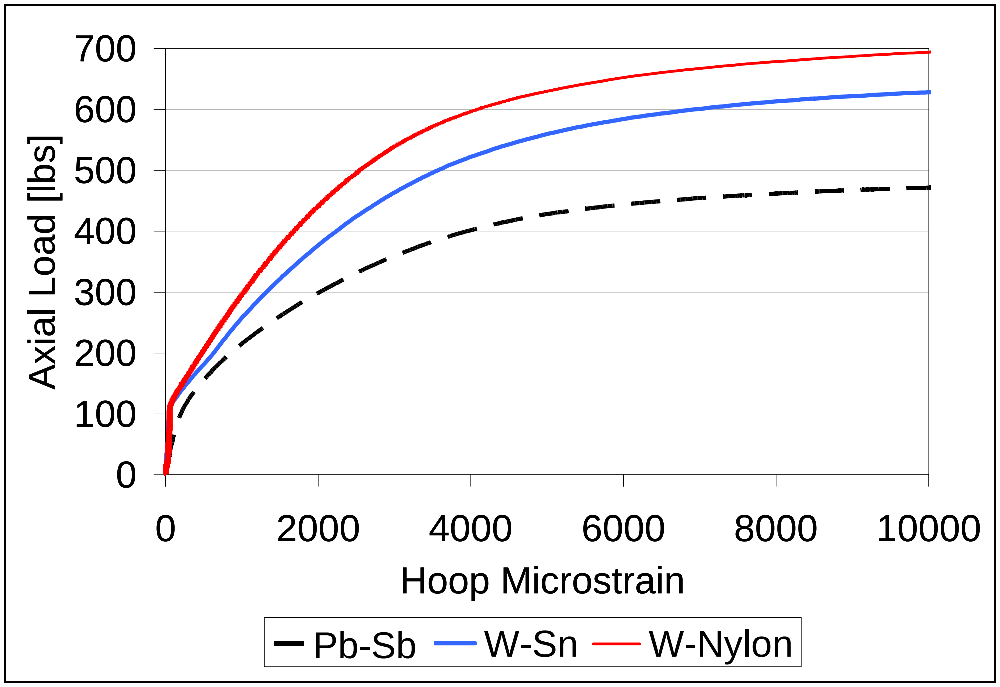

Figure 5. Plot of the average response of the sheathed slug test for each of the three materials.

Table 1. Table of the experimentally obtained modulus, compressive yield, and Poisson's ratio values for lead-antimony, tungsten-tin, and tungsten-nylon projectile cores.

Projectile Core	Modulus (Msi)	Compressive Yield (Ksi)	Poisson's Ratio
Pb-Sb	2.0	2.1	.42
W-Sn	7.68	2.8	.32
W-Nylon	0.65	4.8	.31

the yield strength of the slug materials is driving the response of the sheathed slug materials. This testing gives a quasistatic representation of the effect of slug material on the behavior of small-caliber ammunition. In order to get an estimate of what happens in-bore, numerical simulations are required.

3. Numerical

3.1 Numerical Simulations

Finite-element simulations were generated to evaluate the relative response of each material during launch in a weapon with a linear rifling profile. Previous research on the in-bore performance of Pb-Sb and W-Nylon in a smooth bored barrel has shown that there are differences in how the projectile obturates (*2*). During launch of a small-caliber projectile, several events happen to the projectile in order for the weapons to both obturate and the projectiles to spin.

Figure 6 shows the radial displacement of the M855 projectile at peak acceleration. Several key features can be seen on this figure. The first is that the jacket in the rear portion of the projectile by the boattail is clamping down on the back of the slug. The second key feature is that there is a slight gap in the front of the projectile between the jacket and the core. The presence of the gap demonstrated that the jacket is trying to ride forward on the back of the slug and that the core is being carried by the slug. This is consistent with the relative accelerations as the jacket acceleration is greater than the slug/core acceleration (*2*).

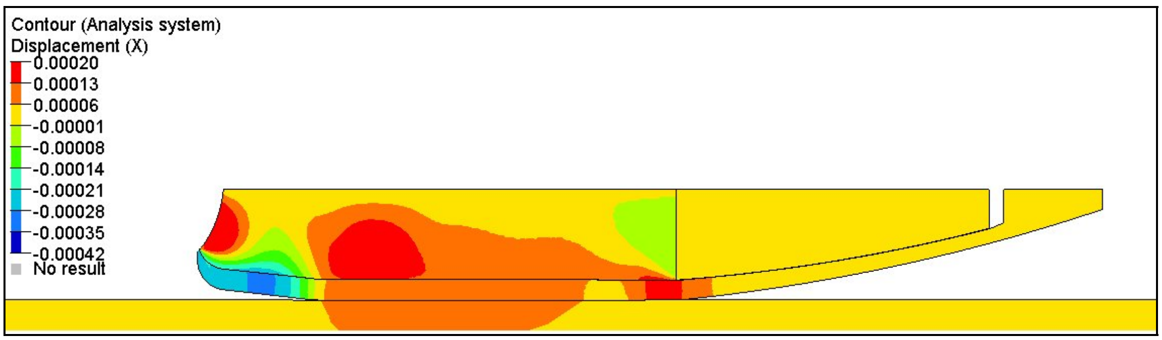

Figure 6. Radial displacement (in) of the M855 (Pb-Sb) projectile at peak acceleration.

Secondly, the figure shows that the cylindrical section of the projectile provides the projectile/bore gas seal (e.g., obturation). Both the front section and rear section of the cylindrical portion of the slug are expanding in the radial direction, forcing the jacket into the bore of the gun barrel. In addition to obturation, this expansion provides the pressure necessary to cause the jacket to flow around the rifling as the projectile engages the lands in the gun. The purpose of the linear rifling model is to evaluate the material effect of this expansion on the stress state at the surface of the land and the groove of the barrel.

The finite-element simulations were performed using LS-Dyna. Due to the nature of a linear rifling profile and the design of the projectile, quarter symmetry was employed. Figure 7 shows the design of the model. The geometry for both the projectile (*1*) and the weapon (*6*) were obtained from their respective technical drawing packages. Appropriate boundary conditions were applied to the model to maintain quarter symmetry. The base pressure-time curve for the M855 was obtained from interior ballistic calculations (*7*). Contact was used between the slug-core-jacket and the jacket-barrel. All of the components within the projectile were allowed to move freely. The rifling profile was that of the M16A2 with the exception that the twist was set to zero, or essentially one turn in infinity. This resulted in a linear rifling profile. The benefit of the linear rifling profile and the quarter symmetry was that the model could be built with the middle of a land and a groove lying directly on the symmetry planes. This allowed for a direct

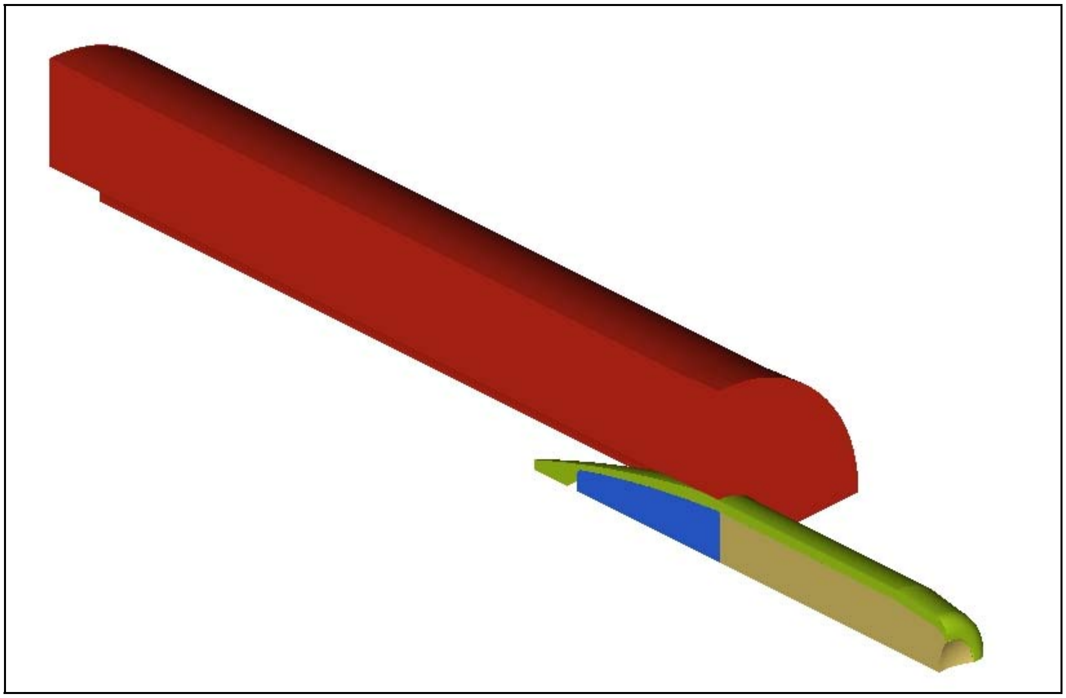

Figure 7. Design of the finite-element simulation to evaluate the effect of the slug material on the lands and the grooves.

evaluation of the radial stress on the surface of the land and the groove. The model was built with the y-axis down the barrel and the x and z-axes being the symmetry planes. Material properties for each of the slug materials were taken from Weerasooryia et al. (*8*). The properties for the barrel and the core were assumed to be linear elastic steel. The stress-strain for the jacket was from South et al. (*9*). The effect of the different slug materials was evaluated by running the identical model for each case.

3.2 Numerical Predictions

The simulations' results were post-processed in order to evaluate the radial stresses on the lands and the groove at the origin of rifling as the projectile passed by. For each model the same element was selected to evaluate. Model predictions of the radial stress on the land at the origin of rifling for each material are shown in figure 8. The figure shows the radial stress as a function of time. At short times there is no interaction between the projectile and the weapon. Initially, the stress spikes as the projectile begins to engrave just over the steel core. As time increases the stress drops off and then begins to increase again as the slug material becomes inelastic and begins to expand radially toward the jacket. This is the same phenomenon that was presented in figure 6.

Figures 8 and 9 show that there is a definitive effect of the slug material on the in-bore behavior of the projectile. The predictions of the radial stress on the lands at the origin of rifling show that the W-Nylon places a substantially higher stress on the land. The predictions on the groove

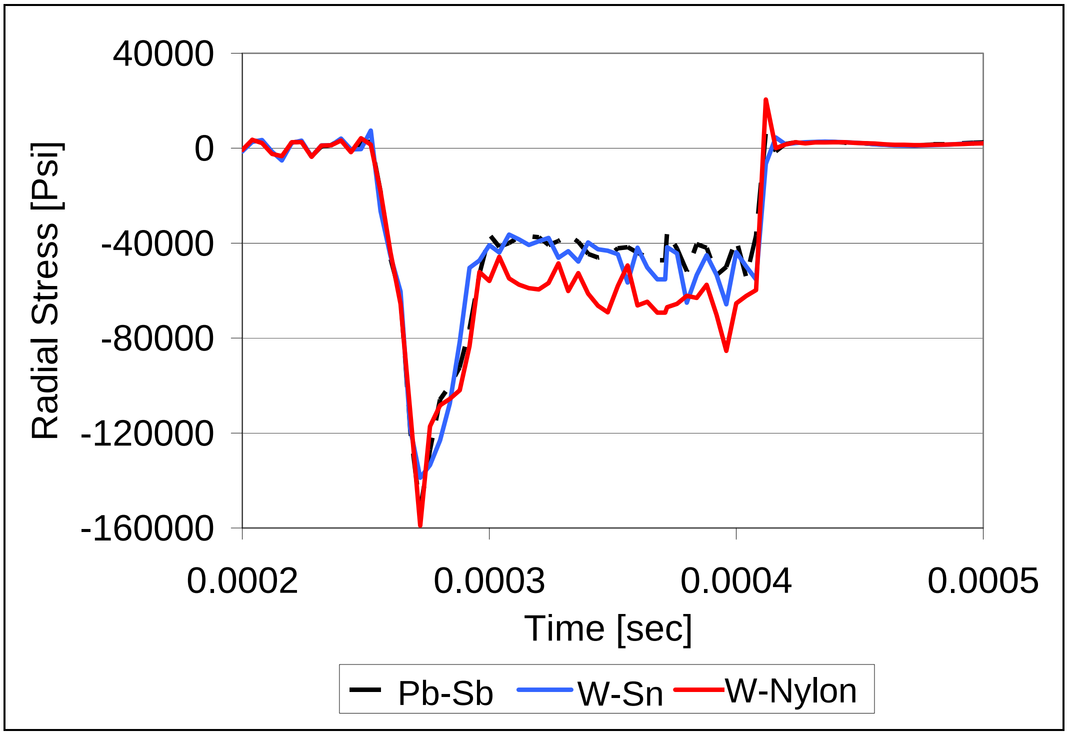

Figure 8. Predictions of the radial stress on the land at the origin of rifling for each slug material.

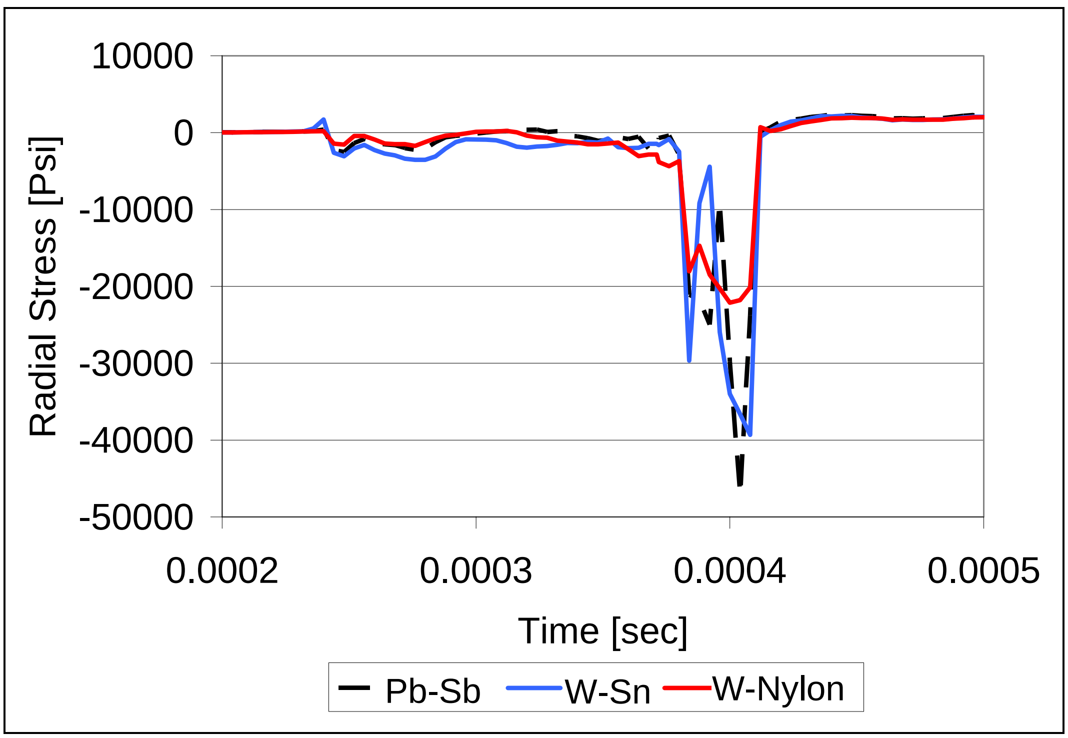

Figure 9. Predictions of the radial stress on the groove at the origin of rifling for each slug material.

show that the lead produces the highest radial stress, followed by the W-Sn and W-Nylon. The net effect is that W-Nylon and W-Sn cores generate stresses on the land and the grooves that are substantially different than that of the Pb-Sb cores.

4. Discussion

The implications of the experiments and the numerical simulations are paramount to understanding the effect of material properties on the projectile performance. The higher stress produced on the lands by the green cores may lead to a greater amount of wear on the barrel. The lower stresses generated on the grooves by the green cores may lead to reduced obturation of the propellant gases. Reduced obturation would result in an increase in thermochemical erosion of the barrel. The result of these changes in the in-bore behavior may affect barrel life and the resulting accuracy. These stresses are linked directly to the mechanical properties of the green cores.

In the case of the sheathed compression samples, the yield strength appeared to dominate the results of the test. The linear engraving model showed the same trend, with the behavior tracking the changes in the yield strength between the different cores. Previous research by South and Newill (*10*) has shown that the high yield strength of W-Nylon compared to Pb-Sb results in a lower level of plastic strain in the core at peak acceleration. In this case, it appears that the yield strength of the slug is controlling the engraving of the jacket into the rifling.

5. Conclusions

The drive to produce environmentally friendly “green” ammunition has shifted focus to alternate materials for the lead cores in small-arms ammunition. Candidate materials such as tungsten-nylon and tungsten-tin have been evaluated as possible replacements. Experiments were conducted on sheathed and unsheathed core samples to determine their compressive response. It was found that the yield strength of the slug material is the controlling property on the structural response of the copper jacket. Finite-element simulations evaluated the relative response of each material during launch in a weapon with a linear rifling profile. The predictions of the radial stress on the lands at the origin of rifling show that the W-Sn and the W-Nylon place a substantially higher stress on the land. The predictions on the groove show that the lead produces the highest radial stress followed by the W-Nylon and W-Sn. The net effect is that W-Nylon and W-Sn cores generate stresses on the land and the grooves that are substantially different than that of the Pb-Sb cores. These stresses are directly related to the material properties of the slugs and may effect both barrel wear and performance.

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